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Review

Impacts of protected vegetable cultivation on climate change and adaptation strategies for cleaner production – A review

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ABSTRACT

Here we provide a critical and comprehensive review of recent developments in the impact of protected cultivation on climate change and map the factors involved. Some possible ways to reduce greenhouse gas emissions are suggested and some sustainable adaptation strategies are indicated. We expand our survey of the existing research to the entire production system, including greenhouse structure, energy, electricity, growing media, and fertilizers. Technical and conceptual innovations are discussed, along with structural solutions, such as screenhouses. We believe that this work will contribute to facilitating reductions in direct and indirect emissions from the greenhouse gas inventory while simultaneously reducing the waste from protected cultivation systems. Moreover, we believe that this review will shed new light on some of these approaches and suggest new ways for cleaner production in controlled-environment systems. The transition to sustainable protected cultivation systems needs to be economically viable – innovative adaptations are required. We recommend adaptations such as maximum insulation, smart climate control, sustainable energy sources such as biogas, photovoltaics and geothermal energy, as well as new concepts for crop production to reduce the impact of protected cultivation on climate change.

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Abbreviations: CC, climate change; CHP, combined heat and power unit; GHG, greenhouse gas; GWP, global warming potential; LCA, life-cycle assessment.

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1. Introduction

Throughout history, the earth's climate has been continuously subjected to changes. Hot periods have been succeeded by colder ones that developed into ice ages. Many of these fluctuations occur naturally, through changes in solar radiation and volcanic eruptions. However, the rapid temperature rise since the industrial revolution has mainly anthropogenic causes (Crowley, 2000). Recent climate change (CC)[1] derives from the emission of greenhouse gases (GHGs), such as carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4), by the industry, agriculture and the population. GHGs absorb solar radiation and heat up the atmosphere, known as the greenhouse effect (IPCC, 2013). Hence, one of the main modern-day challenges is mitigation of GHG emissions. Agriculture/horticulture and CC have a dual interaction. On the one hand, the environment is affected by activities associated with agricultural food production, which contributes to CC; on the other, the impacts arising from such activities backfire by changing the environmental conditions, thus affecting agriculture and horticulture (Gruda et al., 2019).

Protected cultivation is an agrotechnology that has become highly popular among growers. Covering the crop allows regulation of macro- and microenvironments, facilitating optimal plant performance, extension of production duration, induction of earliness, and obtaining higher and better quality yields (Gruda and Tanny, 2014, 2015). A spectrum of covered structures is used by growers, depending on the crop, the climatic region and the anticipated benefit. There are different classifications for greenhouses, on the basis of: cover (porous screen, flexible plastic, rigid plastic and glass), form and structure (tunnel, even span, ridge-and-furrow and contiguous), heating (with or without it), and climate control and technology used (low- or high-tech). Some variations exist within each of these classes.

On the basis of cover and equipment, various types of structures are used as protected cultivation systems (Fig. 1). The simplest type is a permeable porous screen that directly covers the plants to protect them mainly from solar radiation and hail (Fig. 1a). A more advanced type of cover is the screenhouse, which consists of a screened roof and sidewalls (Figs. 1b and 2a). If covered by an insect-proof screen, it protects the crop from insect invasion (Tanny et al., 2003), whereas if it is covered by a shading screen, it protects against supra-optimal solar radiation and hail, and reduces wind speed (Tanny et al., 2006). Black screens are also used for shading purposes and they are usually deployed during the warm season and removed when radiation load decreases. An example of plastic tunnels covered with 40% black shading screens is presented in Fig. 2b.

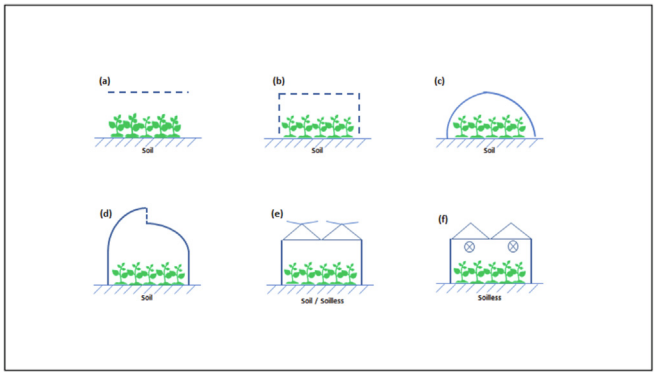

Fig. 1. Schematic drawings of common protected cultivation systems: (a) A horizontal screen cover in the roof only; (b) A screenhouse with screened roof and sidewalls; (c) A plastic tunnel; (d) A naturally ventilated greenhouse with a vertical roof opening; (e) A Venlo glasshouse with inclined roof openings; (f) A greenhouse with active climate control, usually with a soilless culture system.

Naturally ventilated tunnels or greenhouses are covered by an impermeable transparent plastic film, which may include roof and/or side vents that allow natural ventilation by wind or buoyancy effects (Fig. 1c and d). In Northern European countries, such structures are covered by glass for higher radiation transmittance. The Venlo greenhouse, for instance, is a common type of glass greenhouse, equipped with inclined roof openings for natural ventilation (Fig. 1e). The most sophisticated structure on the basis of environmental climate control and technology used is the so-called high-tech greenhouse, which allows a wide range of climate-control strategies, such as heating, cooling, humidification/dehumidification, additional lighting, etc., and plant growth manipulations. In most cases, soilless culture systems are applied in such structures (Fig. 1f). Synonyms are “controlled-environment agriculture” and sometimes “controlled-environment system” (Gruda and Tanny, 2014). All approaches currently coexist in worldwide horticulture.

The area of controlled-environment systems in screenhouses and naturally ventilated greenhouses in the Mediterranean region and in countries with mild climate conditions is constantly increasing. The largest producers in Europe are Spain and Italy, with a total of 54,000 ha (Palomino and Miguel, 2017) and 33,000 ha (Timpanaro et al., 2015), respectively. In the Almeria region of southern Spain, protected cultivation in simple naturally ventilated greenhouses has expanded rapidly in the last few decades (Castilla and Hernandez, 2005).

In contrast to simple constructions, high-tech greenhouses and glasshouses involve a multitude of technical devices. The degree of technology might differ among growers and regions, but the higher it is, the more expenses are to be expected, offering the opportunity for better climate control and overall more efficient processes. For instance, the Dutch greenhouse industry is one of the most sophisticated in the world and with around 9000 ha (CBS, 2018), they have the largest area under high-tech glasshouses in Europe. A distinguishing feature of greenhouse production in such systems is the large amount of energy consumption for heating during the cold season, artificial lighting (Antón et al., 2012), postharvest transport, packaging (Theurl et al., 2017), and the use of fertilizer and growing media. Consequently, high amounts of GHG are produced and emitted from such protected cultivation systems.

The number of scientific publications that have analyzed the effects of horticulture on CC and *vice versa* have rapidly increased in the last few decades (Aleixandre-Benavent et al., 2017). A number of studies have shown that protected cultivation substantially contributes to GHG emissions and CC. In previous reviews, Bisbis et al. (2018b) and Gruda and Tanny (2014) briefly described the

Fig. 2. a) Pepper plants in a 17-mesh insect-proof screenhouse, in the Jordan Valley region of eastern Israel. The photo was taken on October 10, 2018, about two months after pepper plantation. The meteorological sensors are used to measure internal climate conditions (Photo: Tanny, private collection). b) Plastic tunnels for pepper cultivation in the Jordan Valley region, Israel. The tunnels are externally-covered with a 40% black shading screen during summer, as seen in the photo. The shading screen is removed in October, and is deployed back in spring when high radiation load resumes (Photo: Tanny, 2015; private collection).

effect of controlled-environment systems (i.e., greenhouses with active climate control) on CC. However, protected cultivation includes a multitude of concepts, such as glasshouses, plastic houses and tunnels or screenhouses, and a multitude of aspects such as energy use for heating, fertilizer and pesticide use, and choice of plant substrates. Due to political pressure and high fuel prices, new energy-saving greenhouse concepts and technologies are being developed to reduce GHG emissions from protected horticulture. Combining these innovations creates holistic approaches.

The aim of this paper is to review the impacts of protected cultivation on CC and evaluate possible adaptation options. Up until now, this information has remained scattered among many published studies. One of the goals of this review is to summarize those impacts in a unified framework. Therefore, we expand the existing research with a critical review across the entire production system, including greenhouse structure, energy, electricity, growing media and fertilizers. Moreover, adaptation strategies that minimize or mitigate the contribution of protected cultivation systems to CC are presented. We believe that the broad overview presented here will contribute to cleaner and more sustainable horticultural production.

2. Materials and methods

The focus of this study is, on the one hand, to identify the impacts of protected cultivation on CC, and on the other, to review available suggestions for sustainable adaptation strategies that will reduce or mitigate these impacts and enable cleaner food production by these systems. With this in mind, we conducted a systematic literature review, examining published articles from 1990 to 2019. The review is based on literature from temperate regions in the Northern hemisphere as well as on the Mediterranean basin. However, sometimes we use scientific literature from other regions, such as semiarid or arid districts in China. The literature search was conducted using the following academic databases: Web of Science Core Collection platform from Clarivate Analytics, Scopus and ScienceDirect from Elsevier, ResearchGate from the company with the same name in Berlin, and Google Scholar from Google. Several keywords were chosen to obtain a wide number of search results: “climate change” OR “climate changes” OR “climatic change(s)” OR “CO_2”, OR “Adaptation”, OR “LCA” AND “Impact(s)”. These keywords were combined with “protected cultivation(s)”, “protected crop(s)”, “greenhouse vegetable(s)”, “greenhouse technology”, “screehouse(s)”, “controlled environment agriculture”, “controlled environment system”, “vegetable production”, “vegetable(s)”, “product quality”, or “waste”. The terms were included in quotation marks, in combinations with AND, e.g. “climate change” AND “protected crop(s)”, to guarantee higher precision in the obtained records. All keywords were used in all four databases.

Based on our research question and review objective, we first searched for peer-reviewed studies in protected cultivation, related to CC. Here, we limited the search to journal articles, and omitted gray literature such as books or book chapters, conference papers, etc. We refer to other than peer-reviewed literature only in exceptional cases. Titles and abstracts from more than 1000 articles were screened and evaluated before selecting the relevant papers. A major selection criterion was the inclusion of quantitative information in the paper. We selected studies including topics on (i) the effect of protected cultivation systems on CC, (ii) adaptation strategies of protected cultivation systems sustainable to CC. We compared the remaining articles with each other, and categorized them according to relevant keywords, as presented in the structure of this review. Moreover, we summarized the conducted research, critically analyzed the content of over 100 studies, abstracted the important features, and identified challenges for future research. The impact of CC on controlled-environment systems will be reported in another paper (Gruda et al., 2019).

3. Results and discussion

3.1. Impacts of protected cultivation on environment, harmful emissions and CC

One of the most widely used methodologies for evaluating environmental impacts in terms of GHG emissions and the consumption of natural resources is the life-cycle assessment (LCA), which is guided by the International Organisation for Standardisation (ISO) and has been applied successfully for agricultural and food systems in recent years (Girgenti et al., 2014). Muñoz et al. (2008) conducted a LCA to compare the environmental impacts of

greenhouse vs. open-field tomato production in the Mediterranean region. If properly managed, controlled-environment systems had a smaller environmental impact than open-field crops in most of the evaluation categories considered. This is because most of the impact categories studied were adversely influenced by the lower production in open fields compared to protected cultivation systems. Furthermore, less water consumption is needed in greenhouse production, e.g., 24.2 L kg^{-1} tomato in a greenhouse compared to 42.8 L for an open field (Muñoz et al., 2008; Montero et al., 2009). These results are in accordance with the findings of Ntinas et al. (2017), who reported a water consumption of 43.7 and 60.0 L kg^{-1} tomato produced in an open field in Greece, using ground or surface water, respectively. Torrellas et al. (2013) reported a water-use efficiency of 14.0 L kg^{-1} in a heated greenhouse in Holland and 28.8 L kg^{-1} in an unheated greenhouse in Spain.

Concerning screenhouses, only a few studies have investigated their effects on GHG emissions, which directly affect CC. One recent study (Xu et al., 2017) studied the effect of cultivating flood-irrigated rice under insect-proof screens in China on the emissions of the GHGs CH_4 and N_2O. Results showed that in comparison to the uncovered treatment, the screenhouse cover decreased CH_4 and N_2O emissions from rice by 6.58–18.73 and 2.51–21.35%, respectively, and the global warming potential (GWP) by 6.49–18.65% (Xu et al., 2015; Liu et al., 2016). Although rice yields under screenhouse cultivation declined, it is worth noting that the yield-scaled CH_4 and N_2O emissions and GWP also decreased. Therefore Xu et al. (2017) concluded that cultivating plants in screenhouses is an optional method in response to the pressure of reducing GHG emissions.

Below, some environmental concerns related to the production of horticultural crops in greenhouses, such as the nature and form of the energy used for operating the greenhouses, the construction itself, fertilizer and substrates used to grow plants are presented.

3.1.1. Energy required for operating protected cultivation systems

In temperate regions, controlled-environment systems are characterized by large amounts of energy consumption for heating during the cold season. This consumption ranges from 500 MJ m^{-2} in southern France to over 1900 MJ m^{-2} for Nordic countries, such as Finland (Bakker et al., 2008). Large amounts of energy consumption are related to high GHG emissions, e.g., 6.8 Mt CO_2 eq. y^{-1} in the Netherlands (Hemming et al., 2017). In temperate climates, heating and artificial lighting are the greatest environmental concerns (Antón et al., 2012) (Table 1), followed by postharvest transport and packaging (Theurl et al., 2017).

Baytorun and Zaimoglu (2018) reviewed climate control in Mediterranean greenhouses. Based on the region's climate data, they reported that greenhouses require heating from November to March, ventilation and shading from February to May, and cooling from June to September. To maintain day/night temperatures of 18/16 °C, the annual heating energy requirement of polyethylene greenhouses ranges from 340 to 920 MJ m^{-2}. Due to the high cost of cooling, most greenhouses on the Mediterranean coastline remain idle during the summer months.

Tomatoes imported from Spain can have two to four times lower GWP than those produced locally under intense heating in Austria (Theurl et al., 2014) and in the UK (Webb et al., 2013). However, even unheated greenhouses have a GWP equivalent to 240 g CO_2 eq. kg^{-1} tomato (EUPHOROS consortium, 2010), with fertilizer and substrate use being the major concerns ((Antón et al., 2005b). For the Mediterranean region, where heating requirements are lower, a LCA showed that changing greenhouse vegetable production in Spain from conventional to organic would reduce the CO_2 emission for a 100-year time horizon from 215 to 178 g CO_2 eq. kg^{-1} product (Aguilera et al., 2015). These values are relatively low as compared to vegetables cultivated in heated glasshouses in the colder regions of Northern Europe. According to Eigenbrod and Gruda (2015), the motto for future food production should not be “local at any price” but “as sustainable as possible”. This will prevent food production under high costs and energy consumption.

In countries like the Netherlands, about 25% of the electrical energy in the public grid is produced by hard coal, which is related to problems such as the disposal of coal mining waste (Antón et al., 2012). The use of electricity in a greenhouse for ventilators, fans, assimilation lights, circulation pumps, etc., can thus become a major environmental concern and contributor to global CC. Due to the use of supplementary lighting, ornamental production usually has a higher environmental impact than, for instance, tomato production (Pluimers, 2001). This is due to the high GHG emissions during electricity generation in the public grid. Cyclamen is one of the major ornamentals grown and traded worldwide. A LCA by Russo and De Lucia Zeller (2007) showed that during the production of potted cyclamen, electricity is the second highest contributor to GWP due to the application of supplementary lighting. In northern countries, where artificial lighting is required, an estimated 200 W m^{-2} of electricity is used for that purpose.

3.1.2. Greenhouse structure

The greenhouse structure has a large influence on global warming. During the production of the structure itself (using steel and concrete), high CO_2 emissions are delivered into the atmosphere (Muñoz et al., 2008). The emissions that arise from the

Table 1
Environmental impacts of open field and greenhouse systems and their heat supply for 1 t of tomato production or 1 MJ of energy.

Production system	Energy source (heating)	GWP (kg CO_2 eq.)	Functional unit	Substrate	Region	Reference
Open field, unheated	–	50.26	1 t tomato	Soil	Khuzestan, Iran	Zarei et al. (2017)
Plastic tunnels, unheated	–	65.82	1 t tomato	Soil	Khuzestan, Iran	Zarei et al. (2017)
		508	1 t tomato	Soil	Mediterranean, France	(Boulard et al., 2011a,b)
Plastic tunnels, heated	Fossil	0.087	1 MJ of energy	–	Mediterranean, Italy	Russo et al. (2014)
	Geothermal + grid for electricity	0.217	1 MJ of energy	–	Mediterranean, Italy	Russo et al. (2014)
	Geothermal + PV for electricity	0.063	1 MJ of energy	–	Mediterranean, Italy	Russo et al. (2014)
Plastic greenhouse, unheated	–	617	1 t tomato	Soil	Mediterranean, Spain	(Romero-Gámez et al., 2017)
Plastic greenhouse, heated	Fossil	250	1 t tomato	Soilless	Mediterranean, Spain	Torrellas et al. (2012)
	Fossil	1620–1860	1 t tomato	Soilless	Mediterranean, France	(Boulard et al., 2011a,b)
	Fossil	2310–2360	1 t tomato	Soilless	Western Europe, France	(Boulard et al., 2011a,b)
Glasshouse, heated	Fossil	780	1 t tomato	Soilless	Mediterranean, Spain	Antón et al. (2010)
	Fossil	1810–2070	1 t tomato	Soilless	Mediterranean, France	(Boulard et al., 2011a,b)
	Fossil	2060–2100	1 t tomato	Soilless	Western Europe (France)	(Boulard et al., 2011a,b)
	Fossil	3300	1 t tomato	Soilless	Northern Europe, Sweden	Carlsson-Kanyama (1998)
Closed greenhouse, heated	Heat regain	nd	nd	nd	nd	nd

GWP = Global Warming Potential, including CO_2, N_2O and CH_4 emissions; expressed as CO_2 equivalents. PV = Photovoltaic, nd = no data.

manufacturing of construction parts could be reduced by changing the nature of the materials. Antón et al. (2012) and Theurl et al. (2014) reported that the construction of a Venlo greenhouse can contribute about 10% to the total environmental impact of a tomato crop cultivated within such a greenhouse. This is mainly due to emissions of phosphates, sulfur dioxide and nitrogen oxides (NO_x). The high amount of steel and aluminum in the frame, as well as the glass, have a high energy demand during manufacturing and therefore, among construction materials, make the largest contribution to the GWP, about 53 kg CO_2 eq. t^{-1} tomato, followed by plastics and concrete.

According to Torrellas et al. (2013), the structure is the major burden in unheated multitunnels, followed by electricity, substrate, fertilizers and water, whereas the requirements for other resources are minimal. Therefore, the structure had the highest contribution to the GWP, with 37% of the impact, followed by auxiliary equipment and fertilizers at 30.8% and 30.6%, respectively (Torrellas et al., 2013).

3.1.3. Fertilizers and nitrogen emissions

N_2O is considered to be extremely damaging to the ozone layer. One ton of N_2O is equivalent to nearly 300 tons of CO_2, with a residence time of about 170 years in the stratosphere (IPCC, 2013). About 80% of anthropogenic N_2O emissions are attributed to agriculture (UNEP, 2019).

Intense and year-round crop production, high N-fertilizer application, suitable temperatures, and frequent irrigation make the greenhouse system an ideal environment for high N_2O emissions. The main source is synthetic N fertilizer. According to the LCA of tomato production in a Venlo greenhouse by Antón et al. (2012), fertilizers have a GWP of 4.8 kg CO_2 equivalents t^{-1} tomato. Fertilizer use involves environmental impacts from the manufacturing process as well as emissions of N_2O, NH_3 and NO_x during and after application. The production of N fertilizers accounted for 57.2% of the GWP, while 36.5% was attributed to application emissions (Antón et al., 2012).

While many studies on the release of N_2O in vegetable production have been published for open fields (e.g., Rashti et al., 2015; Hénault et al., 2012; Liu et al., 2017), studies on N_2O emissions from crop production in greenhouses are rather rare. Daum and Schenk (1996) investigated gaseous N_2O and N_2 emissions from closed-loop rockwool systems, used as a substrate in hydroponic vegetable production, and found that 12.4% of the N input is emitted by the substrate. Gaseous N losses were nearly twice as high in the summer than in the autumn due to different crop growth stages and the higher temperature of the substrate in summer. In addition, the growth of green algae on the substrate surface stimulated the production of N_2O (Daum and Schenk, 1996). Finally, the reuse or long-term use of rockwool increased N_2O emissions 3.8-fold due to bacterial buildup (Hashida et al., 2014).

Zhang et al. (2016) conducted greenhouse experiments with tomato, Chinese cabbage and green soybean to measure N_2O and nitric oxide (NO) fluxes in response to chemical N-fertilizer application in greenhouse cropping systems in southeast China. Annual N_2O and NO fluxes averaged 52.05 and 14.87 μg N m^{-2} h^{-1} for the controls without N-fertilizer inputs, respectively. With N-fertilizer application, both N_2O and NO emissions increased linearly with the amount of applied N. The authors concluded that the input rate of chemical N fertilizer could be reduced to attain satisfactory yield and low N_2O and NO emissions in greenhouse vegetable cropping systems in China. The large variations in the N_2O emission across different vegetable-growing seasons and crop-rotation periods emphasize the necessity of multiyear observations for reliably quantifying and mitigating N_2O emissions from greenhouse vegetable systems (Zhang et al., 2018). Min et al., (2012) measured N_2O emissions from plastic greenhouses in southern China, in which tomato, cucumber, celery and a second tomato crop were grown. The average N_2O-N flux was 117.4 ± 9 μg N m^{-2} h^{-1}, and the annual emission rate was 8.1 ± 0.6 kg N ha^{-1}, which was seven times greater than that from a rice–wheat system in the same area and soils. Furthermore, according to the authors, reducing the amount of applied synthetic N fertilizer by 40% relative to local farmers' normal usage could reduce annual cumulative N_2O emissions by 33% without any impact on yields.

According to Zhang et al. (2018), greenhouse vegetable systems associated with intensive N application and frequent flooding irrigation substantially contribute to N_2O emissions. However, differences between the different irrigation methods significantly affect soil N_2O emissions. For instance, furrow irrigation –widely practiced in China and some other countries, creates an anaerobic environment with denitrification or nitrifier-denitrification processes that in turn produce N_2O, which is released into the atmosphere. In contrast, the soil N_2O emissions in greenhouses were effectively reduced when drip and/or subsurface irrigation was used (Ye et al., 2018). This ultimately reduced the GWP of horticultural production, especially when a closed-loop irrigation system was applied (Table 2).

3.1.4. Substrates

For commercial soilless production of vegetables and cut flowers, stand-alone substrates such as rockwool, perlite or coir are used (Savvas and Gruda, 2018). Nevertheless, peat is the most widely used substrate component in horticulture. Currently, peat accounts for about 80% of the growing media used annually in Europe's horticultural industry (Schmilewski, 2009, Gruda 2012a). However, peat comes from peatland ecosystems, which are very important for carbon sequestration (Gruda et al., 2016). Hence, when peat is used as a substrate, stored carbon is released, negatively affecting the environment and CO_2 balance.

The disposal problems, and the energy consumed during the manufacture of mineral wool, are two main criticisms for using rockwool in the soilless culture industry (Savvas and Gruda, 2018). In a LCA of tomato production in the Netherlands, Antón et al. (2012) reported that substrates were a major contributor to GWP

Table 2
Environmental impacts of vegetable production in soil and substrate culture with closed and open irrigation.

Substrate	Irrigation	GWP (kg CO_2 eq.)	Production system	Functional unit	Reference
Soil	Open	585.19	Open field	1 t strawberry	Khoshnevisan et al. (2013)
Soil	Open	230	Open field	1 t lettuce	Martinez-Mate et al. (2018)
Soilless	Closed	110	Open field	1 t lettuce	Martinez-Mate et al. (2018)
Soilless	Open	91.2	Plastic greenhouse, unheated	1 t tomato	Anton et al. (2005a)
Perlite	Closed	81.4	Plastic greenhouse, unheated	1 t tomato	Anton et al. (2005b)
NFT	Closed	38,700	Greenhouse, unspecified	1 ha tomato	Tewolde et al. (2014)
Modified NFT	Closed	29,800	Greenhouse, unspecified	1 ha tomato	Tewolde et al. (2014)
Rockwool	Closed	30,600	Greenhouse, unspecified	1 ha tomato	Tewolde et al. (2014)

GWP = Global Warming Potential, including CO_2, N_2O and CH_4 emissions; expressed as CO_2 equivalents. NFT = Nutrient Film Technique.

due to the high amounts of energy consumed during manufacturing with a total GWP of 1.4 kg CO_2 equivalents t^{-1} tomato, followed by plastic materials and metals.

Analyzing the LCA of horticultural growing media, QUANTIS (2012) classified peat as having the highest impact on "climate change" and "resources" and mineral wool as having the highest impact on "human health".

3.1.5. Postharvest transport and packaging

According to Theurl et al. (2017), industrial food systems, and particularly vegetable production in Europe are characterized by a sophisticated chronology of postharvest procedures that include packaging, storage and transport. For instance, packaging was a major hot spot for vegetable products, especially when produce was distributed via supermarket logistics (Theurl et al., 2017). Cellura et al. (2012) stated that the use of materials for packaging should be investigated in more detail and ecodesign solutions should be examined. According to the authors, an improvement could be the use of environmentally friendly and recycled materials with low impact.

Postharvest transport is also associated with consumer behavior. Theurl et al. (2017) stated that transport to the farm shop or supermarket by car strongly increases the emission of GHGs. Thus, even organic winter vegetables reached the emission levels of vegetables from heated glasshouses.

Today, some supermarkets have started to forbid the use of plastic bags, in order to improve the sustainability of fruit and vegetable marketing. Reducing plastic material in the marketing chain is definitely a very important issue. However, a differentiation needs to be made: if, for example, paper bags are used only once, their LCA is worse than that of the plastic bags that might be recycled. Therefore, a better option would be the reuse of textile bags.

3.2. Some adaptation tools to control, reduce or eliminate the impact of protected cultivation on CC

3.2.1. Reducing fossil fuel consumption

To minimize CC, GHG emissions have to be reduced, especially as concerns energy use (Tables 1 and 2). In temperate regions, heating greenhouses by means of fossil fuels is the major contributor to GHG emissions and a major drawback for cleaner production. According to Stanhill (1980), energy productivity (kilograms dry matter produced per megajoule energy used) is 16 times less in a heated greenhouse than in an unheated one (Boulard et al., 2011b) (Table 1). Despite the introduction of new developments and innovations, the energy used for heated greenhouses is still high, and this is not only an economic issue, but an environmental one as well (Boulard et al., 2011b). In the future, milder winters will result in reduced energy demand for heating, viz. less GHG emissions—a positive side effect of CC (Bisbis et al., 2018a). Nevertheless, controlled-environment systems will remain energy intensive, so the need for better energy-use efficiency and cleaner energy sources is gaining importance.

3.2.1.1. Minimizing energy losses. The first approach to reducing fossil fuel consumption is to reduce energy losses where possible. Heat that is lost to the outside environment is a nonproductive waste of natural and financial resources and a burden for the environment, which can be avoided by using a number of technical tools and energy-saving strategies.

Greenhouse insulation is one of the most important aspects in reducing energy losses. The covering material is the shell of the greenhouse and its nature determines the degree of interaction with the outside climate. In conventional single-glazed greenhouses, energy losses arise by heat convection and radiation through the greenhouse cover (Bakker et al., 2008). Poor insulation of ventilation windows can increase energy consumption by 20% (Gruda et al., 2009a). According to Bakker et al. (2008), developing materials that combine high thermal insulation values with high light transmission is one of the most challenging issues. A double layer of glass can decrease heat losses by up to 26% compared to single glazing (Bakker et al., 2008); however, the more layers used, the more the light transmission is reduced. This can be overcome by applying an antireflective coating on the glass surface (Hemming et al., 2012). Recently a new type of argon-filled double glass was developed, combining numerous antireflective coatings for maximum light transmission and an anti-emission coating to minimize heat radiation from the greenhouse to the outside (De Zwart et al., 2015). Results showed performance similar to that of single glazing in terms of light transmission, while providing substantially higher thermal insulation.

In the building industry, further energy savings can be realized by creating a vacuum in the space between the two glass sheets or by filling it with high-tech substances, such as phase change material or aerogels (Hee et al., 2015). The application for greenhouses remains relatively unexplored, mainly for economic reasons. Other glazing technologies that originate from the building industry are described by Hee et al. (2015). Dynamic glazing could be of particular interest for greenhouse horticulture as it enables control over properties such as heat conductivity and light transmission by incorporation several high-tech materials. With the incorporation of electrochromic particles, the glass can be "tinted" by excitation with an electrical current. Thus, electrochromic glazing enables switching between high and low heat transfer and light transmission (Hee et al., 2015). In thermochromic glazing, the trigger for tinting is the amount of heat received by the material.

Energy or thermal screens provide an additional barrier between the greenhouse environment and its surroundings, by reducing radiative heat loss through the incorporation of aluminum strips that inhibit transmittance of thermal infrared radiation (IR) to the outside. Thermal screens can save up to 20% on energy but depending on the material and the amount of aluminum, they also reduce light transmission (Bakker et al., 2008). Mobile screens have less impact on the light transmission than fixed screens or double rooves (Bakker et al., 2008). They are deployed at night during the winter to reduce heat losses and folded during the day to allow for light penetration. Transparent plastic screens with IR additives but without aluminum may also remain deployed during the day. Energy screens are an easy and cost-effective way to reduce heat losses and save energy, and can be installed in any greenhouse, even as an upgrade for older constructions (Ruhm et al., 2009). Currently, most vegetable growers use only one layer of energy screen (Gruda et al., 2009a), even though two screens might be more effective, especially when combined with sidewall curtains (Tantau et al., 2015). Due to the higher expense, double screens are so far mostly applied in ornamental production, where such an investment is still profitable for growers.

Major energy losses arise through ventilation in the winter months. During these months, the rapid humidity built up by crop transpiration is conventionally encountered by so-called dry heating. Humidity is evacuated to the outside by ventilation while heating is applied from below the canopy to push out the humid air. This is accompanied by high sensible and latent heat losses, accounting for 10–25% of the total energy lost seasonally (Dieleman and Hemming, 2009). In the past few decades, attempts to reduce energy consumption by keeping windows closed have resulted in the new concepts of closed and semi-closed greenhouses. These are described in detail in section 3.2.2.5.

3.2.1.2. Energy-saving climate-control strategies. Climate control mainly consists of regulating the temperature and relative humidity so that they will be in the optimum range for plant production. In cold regions, this requires energy input for heating and dehumidification. With advanced climate-control computers and innovative climate strategies, energy savings can be achieved, while yield and quality remain high. Energy consumption could be reduced simply by lowering temperature setpoints during the cold season. However, this option often results in reduced yields and product quality (Bakker et al., 2008). Breeding cold-tolerant cultivars could pave the way for such strategies. Kläring et al. (2015) showed, in experiments with tomatoes, that from an ecological perspective, CO_2 emissions can be cut considerably by reducing the heating setpoints without affecting yield and having only a slight effect on the quality of the fruit.

In contrast to climate-control strategies with fixed ventilation and heating setpoints, dynamic climate management sets inside temperature according to a number of external weather parameters. For instance, on days with low radiation, temperature setpoints can be lowered since photosynthesis is restricted by light and plants will not benefit from the extra warmth. When solar radiation, temperature-sum, outside temperature and wind speed are considered, dynamic climate control can save around 10–20% on expended energy (Ruhm et al., 2009). This principle can be extended to the control strategy of thermal screens as well. Usually, energy screens are controlled according to fixed setpoints at sunrise and sunset. However, an extra 4% energy savings can be achieved when screen folding is delayed until radiation levels reach 50–150 $W\,m^{-2}$ (Bakker et al., 2008). Gilli et al. (2017) realized savings of up to 30% by delaying the morning folding of thermal screens until the outside temperature and radiation reached 5 °C and 30 $W\,m^{-2}$, respectively. Otherwise, the screens remained deployed throughout the day.

Another possibility for energy saving is compensating cooler with warmer periods. This is based on the fact that crops react primarily to the average daily temperature rather than to the exact 24-h temperature course (Bakker et al., 2008). Particularly on sunny winter days, this allows for maximum solar gain during the day and less heating at night. On cloudy days, temperatures can be reduced during the daytime and compensated for by more heating at night. The benefits here arise from the possibility of applying thermal screens at night, so less heat is lost during the period of more intense heating (Bakker et al., 2008). Almost all commercial greenhouse control systems are equipped with the temperature-integration feature and could realize 5–15% energy savings, without affecting plant growth and/or production (Elings et al., 2005; Bakker et al., 2008). Savings of up to 35% can be realized depending on which crop is being grown (Gilli et al., 2017). Temperature integration can be applied within limits; however, if thresholds are exceeded, heat or cold stress will result, slowing development and decreasing product quality (Gruda 2005, 2019; Gruda et al., 2018).

Humidity control could further contribute to energy saving. Increasing humidity setpoints by 5% reduced energy consumption by 5–6% in simulations (Bakker et al., 2008). Thermodynamic dehumidification by mechanical devices, such as heat pumps, has been shown to save energy in the range of 14–25% when combined with temperature integration (Gilli et al., 2017). These cooling-based solutions enable regaining latent heat from the vapor and are essential parts of the semi-closed/closed greenhouse concept aimed at avoiding heat loss through ventilation in the winter.

3.2.1.3. Climate-smart approaches. Choosing cold-tolerant vegetable species reduces the necessity for heating. Shifting from warm-season crops, such as tomato and cucumber, to cool-season crops, e.g., leafy greens, could save large amounts on resources for heating during the cold season which, in turn, could drastically reduce GHG emissions (Table 2). However, on highly specialized greenhouse farms, the equipment is adapted to the specific crop. Tomatoes, peppers and cucumbers are grown in rockwool on hanging gutters and high wires, whereas leafy greens are often grown in deep-water systems. It seems that the higher the degree of specialization, the more problematic it becomes to shift among crop species.

According to Neri et al. (2012), several techniques are available to control plant growth in nurseries, which can interfere with the plant-propagation techniques. For instance, different types of plants can be stored in a cold room (at −1.5 °C) for 2–10 months. As a consequence, the plant structure (architecture), the yield potential and the time of fruit ripening can be programmed in the nursery, and plants can be appropriately maintained in the cold-storage facilities up to transplanting in protected cultivation systems (Neri et al., 2012). This technique then leads to a smart climate approach and energy saving.

3.2.2. The use of alternative energy resources

Fossil fuels, such as heating oil, remain the primary input in greenhouse horticulture; consequently, increasing oil prices often hamper the profitability of vegetable production (Gruda et al., 2009a). In the Netherlands, combined heat and power (CHP) units, where heat, electricity and CO_2 are cogenerated by combustion of natural gas, are widely established. This can be more sustainable than using oil, since it produces an oversupply of electricity that avoids using electricity from the grid, the latter strongly depending on coal (Antón et al., 2012). Furthermore, the relatively clean combustion exhausts may be used for greenhouse CO_2 enrichment, although sometimes they need to be purified. Increasing use of CHP units has reduced CO_2 emissions by 2.35 $Mt\,y^{-1}$ in the Netherlands (Hemming et al., 2017). However, fossil fuels by nature release sequestered CO_2 that was not previously part of the atmospheric system. To slow the progress of CC, energy consumption and GHG emissions must be uncoupled. In the long run, a shift to sustainable energy sources will be inevitable to achieve zero-emission production systems. Therefore, Russo and De Lucia Zeller (2007) suggested the use of renewable energy to reduce the long-term impacts of GHGs due to fossil fuel consumption in the generation of public electricity. The recent pronounced interest in global warming and CC has forced politicians to include the issue of fossil fuels on their agenda. As a result, new goals have been set for fossil energy reduction, for instance, the Dutch horticultural industry aims to reduce CO_2 emissions by 30% in 2020 compared to 1990 (Bakker et al., 2008). Some examples of the use of renewable energy are suggested in the following.

3.2.2.1. Biogas. Biogas is obtained through anaerobic digestion of organic wastes, such as feces or plant biomass. It consists mainly of CH_4 and can serve as an alternative to natural gas to run a CHP unit. Biogas combustion produces less nitrous oxides than natural gas due to the absence of ethane and higher contents of paraffinic hydrocarbons (Schettler and Andrews, 2013). This makes it a suitable source of CO_2 for enrichment of greenhouses. In some cases, the exhausts need to be purified of water, H_2S and siloxanes. Production wastes, such as unmarketable yields or biomass residues may, in turn, serve as substrate for the digester to produce biogas (Oleszek et al., 2016). Esen and Yuksel (2013) showed that biogas can serve as a resource for crop production, while crop residues in turn serve to produce biogas.

3.2.2.2. Biomass fuels. Biomass pellets are considered a CO_2-neutral energy carrier since the CO_2 released by burning will be sequestered again by the following crops (Wu et al., 2016). This is a

way of recycling the existing atmospheric and sequestered CO_2, rather than adding CO_2 to the atmosphere from fossil sources. Wood pellets are made of compressed sawdust based on waste from the wood industry and can be used to heat greenhouses (Tantau et al., 2015). If pellet burners were further improved to release less nitrous oxides during combustion, the exhausts could even be used for CO_2 enrichment (Dion et al., 2013). Other sources of pelleted biomass are straw (*Triticum aestivum*), *Miscanthus* (*Miscanthus giganteus*), maize (*Zea mays*), wheat bran, vineyard prunings (from *Vitis vinifera*), hay and sorghum (*Sorghum bicolor*). Use of domestically manufactured wood pellets could reduce GHG emissions in tomato, cucumber, pepper and lettuce production; on the other hand, importing pellets that are transported long distances (e.g., from Canada to the EU) negates the benefits (Wu et al., 2016). Using willow biomass for heating could reduce the global warming impact of greenhouse tomato by 72%, but would require 10 times more land for biofuels than when the same amount of greenhouse tomatoes in the field (Dias et al., 2017). Furthermore, Theurl et al. (2014) reported that even when using woodchips for heating, the environmental burden of heated tomato greenhouses (in Austria) still exceeds that of imported from Spain. According to Galloway et al. (2008), the nature of the biomass fuels should be regarded with caution. High-input crops like maize and sugarcane require high amounts of N fertilizer, with only 30% being converted to biomass. The rising N emissions during the production of biofuels based on the latter crops could thereby reverse the initially intended effect of less CO_2 emissions (Galloway et al., 2008). This again shows the importance of increasing energy-use efficiency in all disciplines of agriculture.

3.2.2.3. Geothermal energy. The earth's crust contains porous layers with hot water (60–100 °C). To utilize geothermal energy, systems extract and deliver this heat to greenhouses via heat exchangers and return the cooled water (20–50 °C) into an underground cold pit at a sufficiently large distance from the warm pit. High investments often force growers to establish cooperatives and collectively run a geothermal power plant (Stanghellini et al., 2019). Once established, operational costs are low. A simulation study by Van 't Ooster et al. (2008) showed that heating a standard greenhouse via geothermal plant substantially reduces fossil energy use; still, a conventional boiler was needed for peak heating demands and was associated with additional CO_2 emissions. Furthermore, the large amounts of electricity consumed by the geothermal heat pumps require sustainable electricity generation. National grids still often rely on coal and other fossil energy carriers, with high GWP. Hence, exploiting electricity from the grid could produce higher CO_2 emissions than burning natural gas for heating, and could be avoided by implementing alternative sources such as photovoltaics (PVs) to feed the geothermal heat pumps (Russo et al., 2014) or hydropower to feed the grid (Wu et al., 2016). In the Netherlands, the optimum share of geothermal heat was 40%, taking into account the tradeoffs, e.g., operational costs, CO_2 source, gas price, and economic competition, to name only a few (Van 't Ooster et al., 2008).

3.2.2.4. The use of PVs for electricity generation. Sunlight can be a useful resource in supplying electricity to a greenhouse. Depending on the season and region, sunlight is more or less abundantly present and a free source of energy. PV technologies capture sunlight and use the stored energy to generate electricity. Over 90% of the PV technologies use mono- and polysilicone-type semiconductors (Cuce et al., 2016). In terms of land use, PV modules are more productive in yielding electricity than biofuels (Poncet et al., 2012). However, with more than 50% of the incoming solar radiation being dissipated as heat, the energy conversion ratio of conventional PV panels is only 9–28%, leaving room for improvement (Cuce et al., 2016). Concentrating PV modules to bundle the incoming light by using, e.g., a Fresnel lens to increase radiation intensity on the active membrane results in a higher efficiency than the conventional design, and can be particularly useful for growers who have restricted land surface area (Cuce et al., 2016).

Integrating solar panels on greenhouse rooftops creates a tradeoff between electricity generation and the plants' light requirements. Bertin et al. (2015) simulated tomato yield in rooftop-integrated PV greenhouses and found yield reductions of 58–70%, depending on the greenhouse construction and planting density. The yield reductions were caused by a shortage of radiation because the PV modules covered 50% of the roof area. In this regard, breeding of cultivars that are well-adapted to low light intensities could be promising; nevertheless, some limitations exist. To maintain sufficient light transmission, less than 30% of the roof area can be used for PV panels (Allardyce et al., 2017). In countries like Morocco, where sunlight is abundant, integrating PV modules over 10% of the roof area increased tomato yield during the hottest months due to a temperature reduction inside the greenhouse and an inhibitory effect on *Tuta absoluta* infestation (Ezzaeri et al., 2018). In regions where light is a limiting factor, plant production could be more feasible under semitransparent or semiopaque PVs, where electricity is generated by absorption of only the non-photosynthetically active radiation (Allardyce et al., 2017). A promising new technology is PV glazing, where a semiconductor film is incorporated into the glass (Allardyce et al., 2017). Similarly, fluorescent solar concentrators may trap photons in a transparent material, e.g., a glass pane, to redirect and concentrate them on an integrated PV film along the edge of the pane (Lamnatou and Chemisana, 2013).

3.2.2.5. Solar greenhouses. Solar greenhouses aim to replace fossil fuels by utilizing the solar heat gain inside the greenhouse (Bot et al., 2005). For instance, Chinese solar greenhouses are used to grow vegetables in the winter without any auxiliary heating, even when the average temperature in the coldest 3 months of the year falls below −10 °C (van Henten et al., 2012; Tonga et al., 2013). Thus, these are completely passive solar greenhouses. The Chinese solar greenhouse design is simple and relatively cheap: a thick wall and partial roof on the north side act as heat sinks, absorbing solar energy during the day and radiating it back into the greenhouse at night. The south-facing roof is a thin transparent surface, normally made of plastic, that transmits the solar rays into the greenhouse during the daytime. An insulating blanket is rolled down over the plastic roof at night to retain heat inside the greenhouse. In the modern structures, the heights of the northern wall and arched struts are 2.5–3.5 and 4–5.8 m, respectively (Teitel et al., 2012; Tonga et al., 2013). Based on analysis of five major climatic regions in China, Wu et al. (2015) used a full carbon cycle analysis to estimate the change in net carbon flux when converting from open field cultivation to cultivation in plastic greenhouses. Results showed that the conversion increased net carbon emissions in the Tibet Plateau region, but reduced net carbon emissions in the other four climatic regions: middle temperate, warm temperate, south subtropical and north subtropical. The authors concluded that vegetable cultivation within plastic greenhouses in these regions could be considered a promising option for carbon-smart intensive agriculture.

In the Netherlands, an annual heat surplus (that needs to be ventilated) from solar radiation of 2000 MJ m^{-2} y^{-1} in summer exceeds the heat requirement of 1000 MJ m^{-2} y^{-1} in winter (De Zwart, 2012). Using this heat in winter means refraining from ventilation, while heat exchangers and heat pumps cool the greenhouse by harvesting the heat. Excess heat available during the

summer is stored and reused during cold periods. Several such concepts have been developed over the years.

In the early 1990s, the idea of closed greenhouses emerged in Europe. Early concepts implied that ventilation windows remain closed throughout all seasons. Using heat pumps and heat exchangers, the excess solar energy is stored in an aquifer system. The aquifer consists of a warm well with a temperature of around 20 °C and a cold well of approximately 7 °C (De Gelder et al., 2012). In summer, the cold well is tapped to cool the greenhouse air and the warmed water is returned to the hot side of the aquifer for seasonal storage. During cold periods (winter or night), the warm water is extracted and heated to 40 °C by a heat pump to provide heating (Bot et al., 2005; De Gelder et al., 2012). This concept could save 25–35% of primary energy (fossil fuels) (De Gelder et al., 2012). The weakness of the closed greenhouse, however, lies in the inability to provide enough cold water in the winter to supply the required cooling load in summer. Furthermore, with the currently available technology, it is not yet economically reasonable to cool a closed greenhouse due to the large amount of expensive electricity required (Van 't Ooster et al., 2008; De Zwart, 2012).

Early concepts of closed greenhouses focused mainly on harvesting a maximal amount of solar energy in the summer. A possible modification of the closed greenhouse is the semi-closed greenhouse, which allows for a certain degree of ventilation in the summer. Van 't Ooster et al. (2008) simulated a semi-closed greenhouse with a heat pump and seasonal storage in combination with a geothermal plant, resulting in the complete exclusion of fossil fuels. By only modestly using the heat pump for cooling, electrical power could be minimized and operational costs reduced (Van 't Ooster et al., 2008). A newer semi-closed greenhouse concept suggests keeping the openings shut during the winter while controlling humidity by technical means. Thus sensible and latent heat losses through ventilation are avoided and may be regained in the cooling process. The harvested heat contributes 25% of the required heating energy, but with a more practicable setup (De Zwart and Speetjens, 2013). Energy-use efficiency increased by as much as 43% due to both yield increase and the reused solar energy (Dannehl et al., 2014). In general, energy savings in semi-closed greenhouses were similar to those in closed greenhouses (De Gelder et al., 2012). Renewable energy sources, such as PV panels or wind power, could feed the heat pump that is required in semi-closed and closed greenhouses (Bakker et al., 2008).

3.2.2.6. Summary of alternative resources. A number of possibilities are available to replace fossil fuel consumption, including geothermal energy, biofuels and the use of solar energy to generate heat and electricity (Fig. 3; new greenhouse concepts that provide holistic approaches are explained in section 3.2.3). However, apart from biogas, none of the aforementioned technologies are able to provide CO_2 to enrich the greenhouse. Furthermore, supplying peak heat loads with a heat pump can be costly. Therefore, growers will always be interested in running combustion engines, to generate CO_2 for the plants. Across Europe, a number of semi-closed greenhouses have been examined by growers, particularly in the Netherlands. However, many continue to use natural gas to produce the electricity for the greenhouse operation and the CO_2 for enrichment. The use of biogas is preferred wherever possible if sufficient amounts can be obtained, to avoid further increase of atmospheric CO_2 concentrations by fossil sources.

3.2.3. Holistic solutions and new concepts of greenhouse cultivation for cleaner production

Growers can adapt new technologies successively, one at a time. However, to avoid high initial investments, stepwise implementation of the next generation cultivation method is preferable (De Gelder et al., 2011). Old constructions can be progressively upgraded, with the growers deciding if a technology is worth implementing (Ruhm et al., 2009). However, when upgrading greenhouses, single solutions often do not have the expected outcome. For instance, when double glazing is employed, the lack of condensation on the cover increases humidity and in turn, the ventilation requirement. The heat losses associated with increased

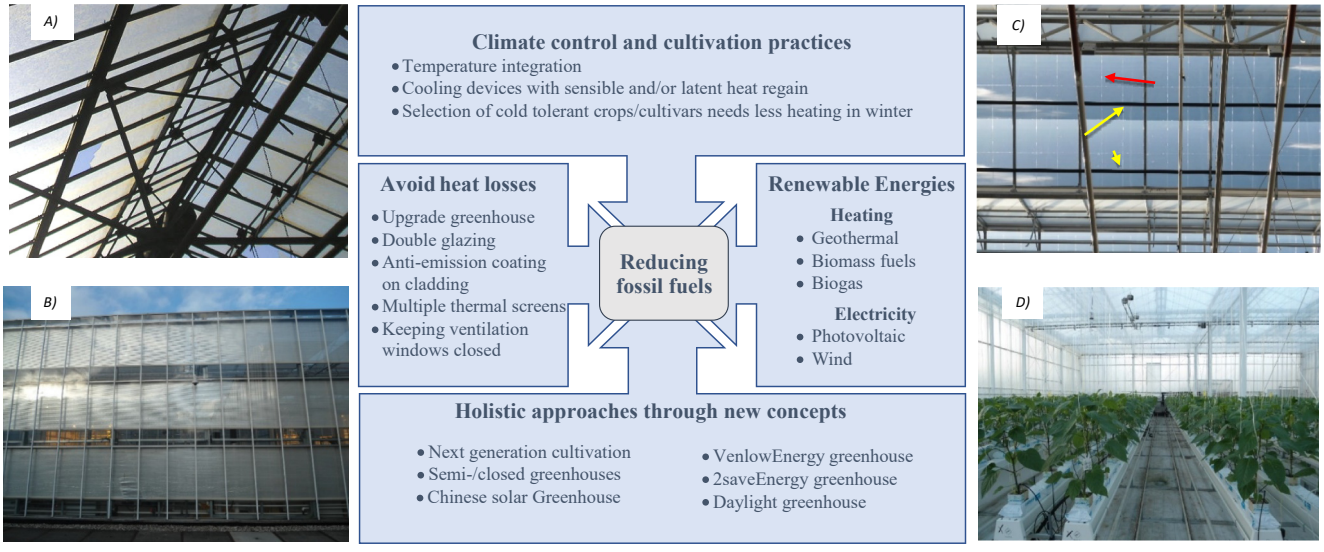

Fig. 3. Reducing fossil fuels is the way to achieve sustainability in greenhouse horticulture. This can be realized through multiple pathways. On the one hand, energy losses are avoided by applying a number of technologies and principles which ultimately result in less fossil fuel consumption. On the other hand, climate control strategies could directly contribute to reduce the amount of energy required to maintain an adequate crop environment. Fossil fuels could also be completely avoided by replacing them with renewable energies for both heat and electricity generation. The adaption and application of all these technologies translate into new greenhouse concepts that provide holistic approaches to ensure no further contribution to climate change. The pictures show some examples of how this can be realized. A) Broken windows enable heat losses to the environment and should be fixed (Photo: Gruda, private collection), B) Energy screens on the sidewalls of the greenhouse (Photo: Bisbis, 2018; private collection), C) Roof of a greenhouse with fresnel lenses (red arrow) incorporated in the glass to concentrate light on moving solar heat or photovoltaic collectors (yellow arrows) (Photo; Bisbis, 2018; private collection), D) 2SaveEnergy greenhouse with special V-shaped screens that remain closed during cloudy winter days (Photo; Bisbis, 2018; private collection).

ventilation negate some of the avoided convection losses, thus reducing the overall savings effect of double covers. Similarly, when thermal screens are deployed, humidity in the greenhouse rises, creating tradeoffs between saving on heating energy and the excess energy required for dehumidification (Bakker et al., 2008). Holistic approaches are necessary to develop new energy-saving greenhouses, which encapsulate a number of new technologies into new concepts (Fig. 3). Several approaches have been undertaken to design a zero-fossil-fuel greenhouse, but so far, only a few have garnered interest (Van 't Ooster et al., 2008). Below, the new trends of zero-fossil-fuel greenhouses are presented.

The next generation growing concept is based on the principle of maximum insulation, which requires new methods of climate control due to elevated humidity. Active dehumidification, higher humidity setpoints, temperature integration, intensive use of thermal screens, forced ventilation, reduced window opening and CO_2 supply are the bases of this concept (De Gelder et al., 2012; Hemming et al., 2017). With deployed energy screens, humidity rises; it is removed by forced ventilation and directed toward a dehumidifying unit. The latter is either an air-to-air heat exchanger using outside air, or an air-to-water heat exchanger with thermal storage (De Gelder et al., 2012; De Zwart and Speetjens, 2013). Thus, a transparent thermal screen can be used during the day and an aluminized screen at night (Marcelis et al., 2014). With that concept, an approximate 30% energy savings can be realized without affecting production levels (Marcelis et al., 2014). Three concepts that rely on next generation cultivation are the VenLowEnergy greenhouse, 2SaveEnergy greenhouse and the ZINEG greenhouse.

The VenLowEnergy greenhouse, described by De Zwart et al. (2015), has a double-glazed argon-filled cover with antireflection coatings on three of the glass surfaces. Light transmission remains similar to that through single glass. An anti-emission coating on the glass surface reduces thermal IR emittance from the cover. To prevent high heat losses through ventilation, the system relies on active dehumidification by an air-to-air heat exchanger. This device mixes outside dry air with greenhouse moist air. The sensible heat originating from the greenhouse is transferred to the cooler outside air. Thus 75% of the sensible heat is regained and returned to the plants, while the latent heat is lost to the environment with the moisture (Hemming et al., 2017). This concept reduced energy input by 50% (500 MJ m^{-2} y^{-1} compared to 1000 MJ $m^{-2}y^{-1}$) while maintaining production levels at 65 kg tomato m^{-2} (Hemming et al., 2017). This means that 15 m^3 m^{-2} of natural gas could be saved annually, somewhat less (10 m^3 m^{-2}) in warm years (De Zwart et al., 2015). To push energy savings beyond 50%, the reduction of crop transpiration at night to prevent conversion of sensible to latent heat is currently being tested (Hemming et al., 2017).

The 2SaveEnergy greenhouse was described by Kempkes and Janse (2016) and was designed to reduce payback time on the investment. The sidewalls are double-glazed and the roof is made of one single glass pane with a second layer of diffuse ethylene tetrafluoroethylene (ETFE) film inside. An extra small window design was chosen with the possibility of introducing warm greenhouse air in between the two layers of the roof cover via the gutter designed to melt snow in the winter. The 2SaveEnergy system relies on active humidity control by intake of outside air. A double layer of V-shaped energy screens prevents heat losses at night. The simulated performance of this concept showed 44% less energy consumption and an annual tomato yield of 63 kg m^{-2} (Hemming et al., 2017).

In the ZINEG (low-energy greenhouse) project in Germany, Tantau et al. (2015) evaluated a plastic greenhouse with highly insulating Perspex walls, a double rooftop cover with a clear and diffuse ETFE film (F-CLEAN®) cladding, and three screens: one thermal screen on the sidewalls, one under the roof and a daytime thermal screen under the roof. This reduced CO_2 emissions of organic lettuce production from 0.9 kg CO_2 m^{-2} in "conventional" organic production to 0.6 kg CO_2 m^{-2} in the ZINEG greenhouse. In tomato, the CO_2 equivalents were reduced from 6.2 to 5.3 kg m^{-2}. The relatively low CO_2 equivalents achieved in this study were due to the application of wood pellets for heating. Overall, this concept could contribute 75–80% energy savings in organic vegetable production (Tantau et al., 2015).

3.2.4. Greenhouse structures

Since CC scenarios generally predict higher air temperatures, it can be assumed that the trend of increasing area of screenhouses and simple greenhouses with passive control of environmental conditions will continue in countries with mild winter climates in the near future as well (Montero et al., 2009). These structures are considered environmentally friendly since their energy consumption, and their GHG emissions, are low.

The emissions that arise from the manufacturing of construction parts could be reduced by changing the nature of the materials, as well as by improving the manufacturing process. On the other hand, the lifetime of structural materials, such as plastic covers, and auxiliary equipment, such as drippers, can be further extended and manufactured from biodegradable materials to reduce waste (see section 3.2.6 as well).

Structural analysis can help lessen the amount of materials required for the greenhouse structure, since, for instance, the footings of locally made greenhouses are mostly designed by experience rather than based on structural analyses (Muñoz et al., 2008; Montero et al., 2009). However, there has been a recent change in this trend; Antón et al. (2014) developed an easy way to calculate the quantity of materials needed, highlighting the importance of different amounts of materials to build these structures.

3.2.5. Good agricultural practices

Good agricultural practices, especially with respect to irrigation and fertilization programs, are necessary to reduce GHG emissions (Table 2). The efficiency of N use is one of the key targets in CC adaptation. This includes all measures to reduce N leaching as well as direct or indirect N_2O emissions. Three pathways can contribute to CC mitigation in relation to the use of N: (i) reduction of direct N_2O emissions, (ii) reduction of nitrate discharges with the leachate and, consequently, (iii) reduction of indirect N_2O emissions, as well as of N-fertilizer requirement in crops.

Today, nitrification inhibitors are widely used to decrease N_2O emissions in many cropping systems. According to Lam et al. (2015), nitrification inhibitors have the potential to mitigate N_2O emission from intensive vegetable production systems. However, according to the authors, to adequately quantify N_2O fluxes, N_2O flux measurements and inhibitor impact analyses have to be carried out *in situ*, i.e., in full-scale greenhouses and not, for example, in small chambers.

The use of soilless culture systems is a generally suitable measure to achieve higher production efficiency (Gruda, 2009). In a study conducted on cut flower production, it was concluded that soilless cultivation reduces the pollutant burden on the environment, above all, by virtue of more than double the productivity relative to soil production (Scarascia Mugnozza et al., 2007). Analyzing the data from a commercial tomato farm in Italy during one summer growing season, Incrocci et al. (2012) reported that the savings by using a closed irrigation system as compared to an open one were 25, 40, 24 and 11% in water, N, P, and K, respectively. Generally, use of closed irrigation systems reduces the

environmental impact of horticultural production (Table 2).

However, when using growing media, there are a number of drawbacks, leaving room for improvement. According to Antón et al. (2012), more focus should placed on the recycling of rockwool and reducing the high energy demand associated with expansion of the minerals during manufacturing. Moreover, sustainable alternative substrates, such as coconut coir, could serve to replace rockwool for fruit and vegetable production (Xiong et al., 2017).

Another substrate, widely used in the ornamental industry, is peat. However, as already noted, peatlands are heavily involved in carbon sequestration. Peatlands contain the largest long-term stores of organic carbon of all terrestrial ecosystems (UNEP, 2019). Over the time span of centuries, peatlands have exerted a net cooling effect on the global radiation balance. Should peatlands begin to degrade on a large scale, this stored carbon could be released, reducing—or even reversing—their climate-cooling effect (Dise, 2009).

Generally, the use of peat substitutes, such as compost (Raviv, 2013), wood fibers (Gruda and Schnitzler, 2006) or biochar (Nemati et al., 2014), can substantially reduce the carbon footprint in horticulture (QUANTIS, 2012, Martínez-Blanco et al., 2013; Steiner and Harttung, 2014, Levesque et al., 2018). Consequently, the international trend is toward the use of local, natural bio-resources and renewable raw materials.

Particularly in industrialized countries, the reuse of wastes has become common (Gruda, 2012b). Barrett et al. (2016) gave a detailed summary of novel materials from industrial, agricultural and municipal waste streams. Renewable fast-growing plants, such as softwood trees, *Miscanthus*, peat moss (*Sphagnum*) from paludiculture or seaweed (*Posidonia*) can also be used as substrate constituents (Savvas and Gruda, 2018). However, the plant cultivation technology has to be adapted to the growing medium's properties. For example, production in wood fiber growing media would not be the same as in peat-based substrates. An adaptation in irrigation strategy and frequency (Gruda and Schnitzler, 2000a; 2000b, 2004), as well as N supply (Gruda et al., 2000), has to be provided. Moreover, the pH value (Jackson et al., 2009), as well as other substrate properties (Gruda et al., 2009b, have to be considered.

Growing media are not just used for the production of ornamentals and vegetables in soilless culture systems, but also for the production of seedlings and transplants for open field cultivation. Usually, the seedlings and transplants are produced under greenhouse conditions on specialized farms. Reducing the amount of growing medium per plant contributes to reducing CO_2 emissions in the production chain of plants. Köbbing et al. (2018) found that sowing and plant propagation in press pots emitted twice the amount of CO_2 compared to seedlings cultivated in trays. The substrate compaction in press pots also played a role.

3.2.6. Waste management

Waste management by composting the biomass and recycling materials is another requirement for future sustainable greenhouses (Montero et al., 2009). Use of recycled materials or extending the materials' lifespan could help reduce the impact of the greenhouse structure on global warming. For example, Girgenti et al. (2014) analyzed the environmental profile of the strawberry industry in northern Italy and reported reductions of 20% in the GWP and nonrenewable energy impact categories only if some of the materials used in the strawberry cultivation chain were replaced with bio-based materials. Bartzas et al. (2015) conducted a LCA study for greenhouse lettuce production in two regions in Spain and one region in Italy. The study also examined the impact of using compost produced from agricultural waste. According to those authors, the use of compost for fertilization of greenhouse crops is a good agronomic and ecological strategy to maintain productivity in terms of yield and improve overall sustainability. Moreover, the phases of compost production, irrigation system, and greenhouse construction and operation were identified as the three main “hot spots” with the highest environmental impact and energy contribution in all studied cases.

The same can be applied to packing. For example, Cellura et al. (2012) suggested that a feasible option might be replacement of the cardboard boxes used for tomatoes and the common plastic crates used for cherry tomatoes with biodegradable plant-based plastics. One advantage to this alternative is that its implementation does not call for any deep behavioral change in the consumer. Furthermore, according to Veeramani et al. (2017), reducing food waste could reduce GWP by up to 8%.

3.2.7. Other adaptation possibilities

In sections 3.2.1–3.2.6 we showed some adaptation tools to reduce the impact of protected cultivation systems that produce year-round high yield vegetables, on CC. In addition, it should be mentioned that the nutritional pattern of high consumption of fresh vegetables is of significant importance through the so-called “displacement effect.” Together with pulses and other plant foods, vegetable consumption indirectly contributes to mitigating GHG emissions from agriculture, by reducing meat consumption, i.e., consumption of saturated fatty acids. The results of an environmental LCA carried out on the average consumption of the most representative food types in the EU-27 indicated that meat and dairy products are the most environmentally burdensome foods (Notarnicola et al, 2017). According to Bryngelsson et al. (2016), a 50% reduction in ruminant meat (beef and mutton) consumption could cut current food-related CH_4 and N_2O emissions to meet the European climate targets. Well-balanced diets rich in grains and other vegetable products are considered to be more healthful than those containing a high proportion of meat and dairy products (Godfray et al., 2010).

Considering the three-pronged approach of health, diet and emissions (Jeffries, 2015), we suggest that year-round sustainable production of fresh protected vegetables is an important cornerstone in addressing the future challenges of CC.

3.3. Assessment of major studies used in this review

Table 3 presents an assessment of the major studies and findings reported in this review, along with the authors' names, tools, aims and results. We believe that this summary table will further assist the readers in scanning this work at a glance to find the relevant papers for a particular research area.

4. Conclusions and future outlook

This review presents the impacts of protected cultivation on CC, as well as some innovation-based adaptation strategies to overcome and/or mitigate those impacts. Although we report on scientific literature from all over the world, we mainly focused on the European region, pinpointing the differences between the temperate north and the Mediterranean south.

The present analysis suggests that protected cultivation has some negative impacts on CC, but also many advantages. By implementing protected cultivation correctly and with caution, and adopting recent findings, most of the risks, constraints and CC impacts can be mitigated. We identified three important points to consider:

Table 3
Assessment of major studies used in this review with methodology, aim and results.

Topic	Authors	Tools and Aims	Results	Assessment
Comparison between open field and greenhouse vegetable production	Muñoz et al. (2008)[1] Ntinas et al. (2017)[2]	Tools: LCA 1 Compare environmental burdens associated with plastic greenhouse and open-field tomato production. 2 Study different tomato cultivation systems, when renewable energy sources are integrated.	1 Greenhouse production has a smaller environmental impact than open-field crops due to higher yield. Greenhouse structure had the biggest influence in the global warming category. 2 Open-field tomato cultivation consumes less energy and emits less GHGs, but water use efficiency is lower. In greenhouses, using solar and biomass energy along with higher marketable yield reduced GHG emissions to the levels of open-field cultivation.	Greenhouse production can contribute to sustainable horticulture. Improving manufacturing materials and integrating hybrid solar energy systems, biomass-pellets, high insulation, novel covering materials and application of energy screens pave the way for cleaner production.
Mediterranean region	Torrellas et al. (2012)[1] Anton et al. (2005a)[2]	Tools: LCA 1 Environmental impact of tomato production in a multi-tunnel greenhouse in Almeria, Spain. 2 Compare soil cultivation and hydroponic systems for tomato production, and an analysis of waste management scenarios.	1 Main contributor to impact categories in the tomato production were structure, substrate, fertilizer and electricity consumption. 2 The main negative impact of greenhouse tomato production derives from the waste of biomass and plastics.	Lifetime of structure materials, e.g. plastic covers, and auxiliary equipment, e.g. drippers should be further extended and manufactured out of biodegradable material to reduce waste. Better management of nutrient supply as well as reduction of fertilizer use is required.
Temperate regions	Antón et al. (2012)[1] Theurl et al. (2014)[2] Russo and De Lucia Zeller (2007)[3] Theurl et al. (2017)[4] Dias et al. (2017)[5]	Tools: LCA 1 Environmental impact assessment of Dutch tomato production. 2 Environmental impact assessment of tomato production in different systems and supply chains. 3 Environmental impact assessment of rose and cyclamen production. 4 Analyze GHG emissions along vegetable supply chains and socio-economic factors in Austria. 5 Impacts of Canadian greenhouse tomato production.	1 Main burdens for environment are heating and the use of rockwool substrate. 2 Heating, packaging, and transport are the most important GHG emitters. New technologies could reduce emissions. 3 Heating had the greatest impact followed by greenhouse structure and equipment and the use of electrical power, in all impact categories. 4 GHG emissions of unheated greenhouses are lower than those from heated systems. A spread of unheated winter production depends on socio-economic factors. 5 Using biomass energy produced locally could reduce global warming impacts by 72% but requires 10 times more land than field production.	In cold climates heating is the main concern to sustainability. Alternatives to fossil energy as well as energy saving technologies need to be promoted. Replacing or recycling rockwool and plastic items is important. Plastics should be of natural origin and biodegradable. Finding substitutes for peat is immediate. New technologies for energy saving must be developed in all levels of the supply chain. Shifting to unheated vegetables to close the supply gap in winter provides an alternative.
Growing media	Gruda (2012a)[1] Barrett et al. (2016)[2]	Tools: Literature review 1 Current and future perspective of growing media in Europe. 2 Review the most commonly used organic materials.	1 The consumption of peat as a growing medium leads to considerable CO_2 emissions. Peat bog re-naturalization contributes to a better CO_2 balance on a large scale. 2 Only a small amount of organic materials has been adopted by the industry. Coir, pine bark, wood fiber, and green composts, have become the used materials in place of peat.	Materials that are available, affordable, environmentally friendly, renewable and/or from high-volume waste streams, will receive the chance to replace peat in the future.
New technology	Montero et al. (2009)[1] Cuce et al. (2016)[2] Ezzaeri et al. (2018)[3] De Gelder et al. (2012)[4] Marcelis et al. (2014)[5] Russo et al. (2014)[6] Torrellas et al. (2013)[7]	Tools: Literature review 1 Review new technologies applied to existing greenhouses. 2 Review on key strategies of energy saving and climate control technologies for greenhouses. 3 Assess impacts of shading by rooftop-photovoltaics on the climate and fruit quality in greenhouses. 4 Describe technical principles of a closed and semi-closed greenhouse. 5 Report on recent innovations in greenhouse horticulture. Tools: LCA 6 Comparison between different greenhouse heating systems. 7 Create a decision support tool for environmental impacts in glass and plastic greenhouses.	1 Adopting new technologies has an unavoidable environmental cost that needs to be compensated by an increase in efficiency of all inputs. 2 Up to 80% energy saving can be achieved through appropriate retrofit of conventional greenhouses. 3 Arranging photovoltaic panels in checkerboard pattern has no effect on agronomic parameters but has negative effects on *Tuta absoluta*. 4 In temperate climates, closed greenhouses reduce fossil energy use by 25–35%, compared to regular greenhouses, with a 10–20% yield increase. 5 Diffuse greenhouse covers increase yields while the use of LEDs is efficient when supplementary lighting is required. Crop modeling is one of the most important tools in horticultural research. 6 Geothermal heat pumps powered by grid electricity have the largest environmental burden. In combination with photovoltaic panels 50% of CO_2 emissions are omitted. 7 A distinctive feature of the tool is the inclusion of multiple environmental impact categories as opposed to only global warming.	Promoting new technologies is a key factor in combating climate change. Reducing fossil fuels often means increasing the use of electricity. Photovoltaic panels as a partial greenhouse cover have a dual effect both for energy production and for plant protection. Closed and semi-closed greenhouses allow for a more controlled climate and higher levels of production, combined with savings in fossil fuel use. However, new technologies will not be adopted only for the sake of preserving the environment. The prerequisite of profitability requires that new technologies are either cheaper or subsidized by governments. Knowledge transfer is a key factor in implementation of such innovations while decision support tools could be a great aid for growers producing at lowest environmental impacts. Crop models could be coupled with climate change models to simulate different scenarios

(*continued on next page*)

Table 3 (*continued*)

Topic	Authors	Tools and Aims	Results	Assessment
Nitrogen emissions and managing the root zone	Galloway et al. (2008)[1] Xu et al. (2017)[2] Daum and Schenk (1996)[3] Hashida et al. (2014)[4] Zhang et al. (2016)[5] Zhang et al. (2018)[6] Ye et al. (2018)[7]	Tools: Literature review 1 Transformation of the nitrogen cycle due to human activities Tools: Experimental research. 2 Effect of cultivation in screenhouses on GHG emissions. 3 Quantify N_2O and N_2 emissions from a soilless culture system. 4 Determine and compare N_2O emissions from rockwool and soil. 5 N_2O and NO fluxes in response to N-fertilizer in greenhouses. 6 Quantify N_2O emissions from greenhouse vegetables and evaluate alternative nitrogen management. 7 Characterize soil N_2O production with drip, subsurface and furrow irrigation.	1 Nitrogen is lost to air, water, and land causing environmental and human health issues, while food production in elsewhere is nitrogen-deficient. 2 The screenhouse cover decreased the CH_4 and N_2O emissions. 3 12.4% of the N input were released as N_2O and N_2. Highest emissions occurred during fruiting. 4 Hydroponics have a lower environmental impact than soil cultivation. Re-use of rock-wool increases fruit yields but accelerates N_2O emissions. 5 Both N_2O and NO emissions linearly increase with N fertilizer application. 6 Reducing N fertilizer rate alone and in combination with a nitrification inhibitor reduces N_2O emissions compared to conventional practices. 7 Drip and subsurface irrigation effectively reduced soil N_2O emissions in soil-cultivated greenhouses.	Optimizing the N use and minimizing its negative consequences requires interdisciplinary approaches and the development of strategies to decrease N-containing waste. Overall, conventional input rate of chemical N fertilizer could be reduced to attain high yield and low N_2O and NO emissions in greenhouse vegetable systems. Fertilizer management should be always considered together with irrigation methods applied. Hydroponic systems should be wisely managed to avoid increased GHG emissions. In spite of moderate yield reduction, cultivation under screen reduced the yield-scaled GWP.

GHG = greenhouse gases, GWP = global warming potential, LCA = Life Cycle Assessment. Superscripted reference numbers (e.g. [1, 2, 3]) link aim, results and assessment with the corresponding literature, applicable only within rows, not columns.

- According to recent studies, energy savings of about 50%, and in turn, the reduction in GHG emissions, can be achieved by implementing the so-called next generation culture methods: better insulation by double cladding and triple screens, following biological and nature-oriented culture techniques more closely, dehumidifying the blown-in air and, if necessary, humidification (rewetting), and “harvesting” of the heat amounts existing in the greenhouse.
- Refraining from fossil fuels for heating and replacing/recycling materials, such as peat, rockwool, plastic materials, synthetic pesticides and chemical fertilizer, are essential for sustainability and CC mitigation. Furthermore, suitable waste management is required.
- Despite moderate yield reductions, cultivation under screens will reduce GHG emissions, while closed and semi-closed greenhouses will allow for a more controlled climate and higher levels of production.

The greenhouse industry is characterized by innovations, some of which are described in this paper. More innovations will find their way into practice in the future. As shown here, greenhouse production has an impact on CC. This is why current and future innovations should not be driven only by economics. We believe that all adaptation strategies will have the chance to be implemented only if they increase business profitability in a sustainable way. This means that they must be simultaneously environmentally friendly and socially acceptable.

Scientific research is the major tool for improving protected cultivation systems toward cleaner production. Research enables a sound examination of innovative approaches, a process which is usually associated with high cost and risk. Some ideas for advanced protected cultivation systems are presented in this review, but knowledge gaps include technologies and strategies for their implementation in the agricultural practice by growers. Since growers' adoption of these technologies depends on the anticipated profit, potential ways of making these systems cost-effective should be sought. Hence, economic aspects of these methodologies should be considered along with their technological innovation. Moreover, a better assessment of the GWP of production activities associated with protected cultivation will assist in mitigating GHG emissions. This knowledge is required for a wide variety of protected cultivation systems—not only those presented in this review, but also those in other regions of the world.

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